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Controlled drainage for improved water management in arid regions irrigated agriculture

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ABSTRACT

In arid regions, controlled drainage is the next logical step towards improving water management in irrigated agriculture and reducing the environmental impacts of subsurface drainage flow. Controlled drainage has been practiced in humid areas for a long time. In this paper traditional subsurface drainage system design procedures are described, followed by alternative design criteria for arid regions and suggestions for system design to include control structures that enable better drain system management. The suggested changes include reducing the installation depth of laterals, accounting for crop water use from shallow ground water in the design, and relaxing the mid-point water depth requirement. Active control of drainage systems in arid irrigated regions is a developing concept that is currently being evaluated around the world. Research in the U.S. and Australia has demonstrated that water tables in irrigated areas can be effectively controlled with various types of structures. Control has resulted in reduced volumes of drainage water and total salt loads discharged. Salt accumulation in the root zone is a consideration in adopting controlled drainage, but other research has demonstrated that it is possible to manage salt accumulation through careful water management.

1. Introduction

Subsurface drainage is used in both humid and arid areas to prevent waterlogging, provide aeration to ensure crop growth, and enhance the trafficability of soil, thus permitting timely soil preparation for planting and harvest. In arid areas, drainage also critically provides leaching capability to control salinity buildup in the crop root zone and soil profile. In the past, subsurface drainage systems were typically designed to discharge water continuously, without regard to the environmental consequences and the effects on crop production. This philosophy has changed in humid areas of the world as the environmental consequences and crop production impacts have been researched.

Subsurface drainage water quality reflects the ground water quality and soil water constituents of the soil being drained. Nitrate and other agricultural chemicals, such as herbicides and pesticides, are commonly found in drainage water in both humid and arid areas. Drainage water in arid irrigated regions may also contain salts, such as NaCl and $CaSO_4$, and elements derived from the soil parent material, such as Se, B, and As. Selenium found in the drainage water originating from the soil on the west side of the San Joaquin Valley was responsible for the environmental problems identified at the Kesterson Reservoir (San Joaquin Valley Drainage Program, 1990; Wichelns and Oster, 2006, this special issue). All of these constituents may have serious negative environmental impacts on the receiving water bodies and downstream water users.

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Agricultural drainage water emanating from the upper mid-western states of the United States has been identified as a nitrate source contributing to a hypoxic zone that exists periodically in the Gulf of Mexico at the mouth of the Mississippi River (Scavia et al., 2003). This led to the formation of a USDA agricultural drainage management system (ADMS) task force composed of federal and state agencies, and university personnel that is evaluating management practices and design modifications of both surface and subsurface drainage systems that may contribute to nitrate load reduction.

Recently, controlled drainage has been identified as a potential management method in humid areas to reduce nitrate loading to surface water. Studies demonstrated significant reductions of nitrate in drainage water discharged from controlled drainage systems as a result of reduced drainage flow and lower concentrations in the shallow ground water (Lalonde et al., 1996). Field data and modeling with Hydrus-2D by De Vos et al. (2000, 2002) and Hesterberg et al. (2006) has shown how the composition of the drainage water varies as a result of changes in the flow pattern associated with transient water tables and variation in concentrations with depth in the soil profile.

Controlled drainage in humid areas of the United States has also been used for subirrigation when water is available (Doty et al., 1975; Fouss et al., 1990). There is also a long tradition of controlled drainage and subirrigation in the Netherlands (Raats and Feddes, 2006). In the subirrigation mode, water is pumped behind the control structure to bring the water table position up to the level of control. Controlling the water table position makes shallow ground water available for crop water use by maintaining soil water content through capillary rise. In situations when water is not available for subirrigation, controlled drainage prevents over-drainage and delays the onset of water stress of crops (Skaggs et al., 1981). It has been used in the coastal plain areas of North Carolina for both subirrigation and prevention of over-drainage (Doty and Parsons, 1979; Doty et al., 1975). The transition from uncontrolled drainage to controlled drainage was in response to environmental concerns and the need for improved water management in humid areas.

For controlled drainage to be effective the soil surface must be nearly flat, so that only very few structures in the drainage system are needed to control the water table depth over large areas. This is the case in the coastal plain of North Carolina and the polders in the Netherlands. One of the problems facing the ADMS task force is that many of the drained areas being evaluated in the study have surface slopes larger than 1%, which creates a problem for effective control over large areas.

The accepted mode of operation for a subsurface drainage system in arid areas has been to let the drains flow continuously. Doering et al. (1982) determined that uncontrolled drainage systems were over-draining land and recommended a shallow water table concept for drainage design to reduce drainage flow. A similar result can be achieved when controls are placed on deeply placed laterals. Controlled water tables provide the added flexibility of control over a wide range of depths and may be used for managing soil salinity and water use from shallow ground water.

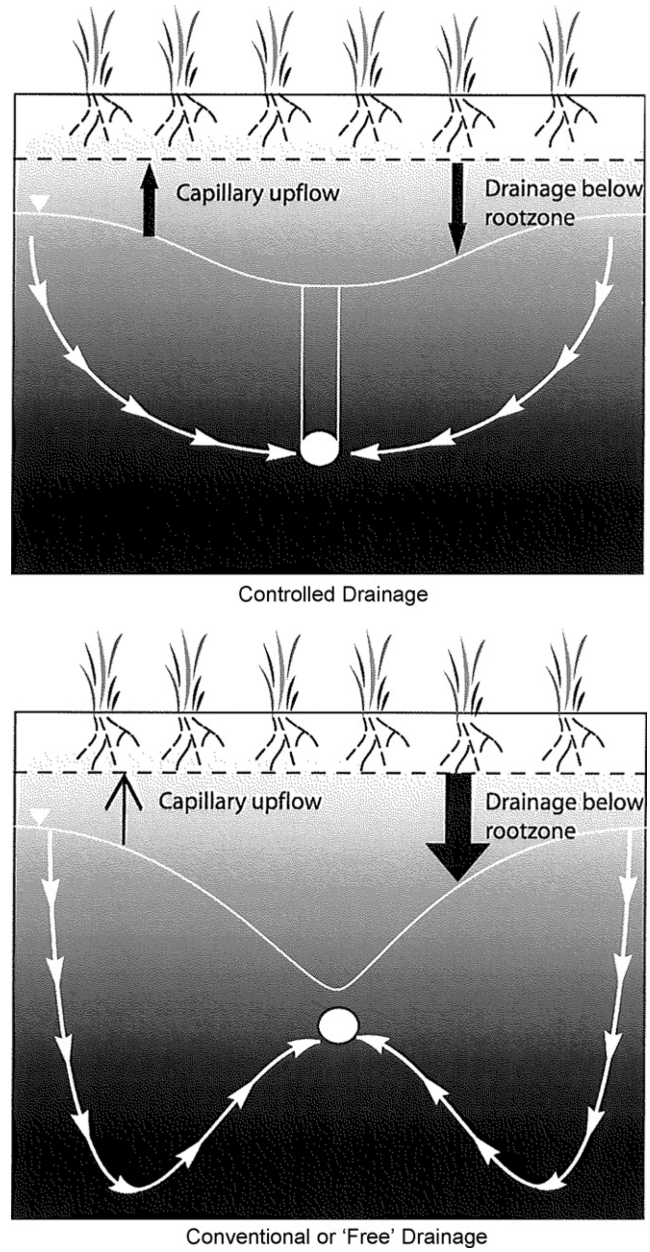

Fig. 1 – Conceptual flow paths in controlled and uncontrolled subsurface drainage systems.

Conceptual flow paths are given for controlled and uncontrolled, conventional drainage systems (Fig. 1). In the uncontrolled system, flow from the drain is continuous and the water table depth is either maintained or lowered, thus reducing potential upward flow that may support crop water use. The flow paths are deep into the soil profile and in situations with increasing salinity with depth the salt load of the drainage water increases. Deeper uncontrolled water tables also allow increased deep percolation from irrigation which translates to increased drainage flow.

In a controlled drainage system the water table is maintained at a shallower depth by a control structure which reduces deep percolation below the root zone by reducing hydraulic gradients and increases potential capillary upflow

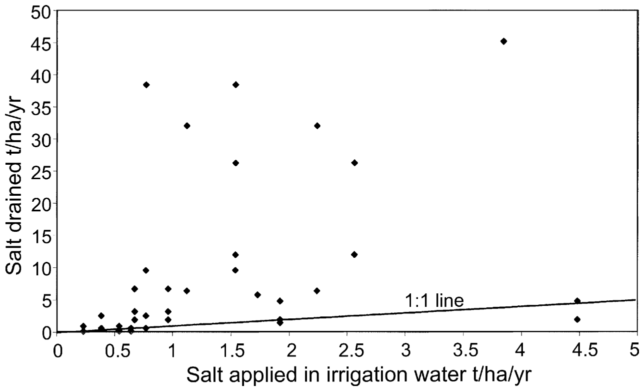

Fig. 2 – Salt loads in irrigation water and drainage from irrigation districts in Australia.

as evapotranspiration depletes soil water in the root zone. The flow lines are shallower than in the uncontrolled system and are more concentrated closer to the soil surface. In soil profiles with zones of lower soil salinity at the soil surface this will result in decreased drain water salinity compared to the uncontrolled system. The reduced drain flows and lower salinity result in much reduced salt loads.

Christen et al. (2001), in a review of subsurface drainage across Australia, demonstrated that the majority of drainage systems were over-draining, as they were removing far more salt than was applied by irrigation water (Fig. 2) and that the drainage rates exceeded those reasonably required to control water tables and waterlogging according to design coefficients. They discussed the need for a new approach to subsurface drainage that applies management to these drainage systems to reduce their downstream environmental impacts whilst maintaining agricultural production.

There are at present no accepted design criteria for controlled or managed drainage systems in either humid or arid zones. Therefore, in Section 2, we first briefly review current design practice for uncontrolled drainage design in both humid and arid zones and their shortcomings. Next in Section 3, we discuss modifications of traditional design criteria in the light of experience of the faults of over-drainage and excessive discharge of salts contained at depth in arid zone soil profiles. The combination of efficient irrigation practice coupled to controlled drainage design is shown to be necessary. In Section 4, some proposed engineering modifications of existing drainage systems are noted and their implications for drainage design criteria discussed. In Section 5, we discuss the management issues and options for controlled drainage. Finally, in Section 6, we review some field studies of controlled drainage experiments to demonstrate current trends and experience.

2. Review of current design practices in the arid irrigated areas of the United States

The U.S. Bureau of Reclamation (USBR) was responsible for the design and installation of drainage systems in many irrigated areas of the arid western United States. The Drainage Manual (U.S. Department of Interior, 1993) was prepared to provide a detailed account of the design procedure, from preliminary field investigation to installation, and remains the basis for most of the subsurface drainage system designs in the arid irrigated areas of the United States.

Data required for design of a subsurface drainage system include soil layering, depth to layers restricting vertical flow, soil hydraulic properties, cropping pattern, irrigation schedule, type of irrigation system, irrigation efficiency, climate data, depth to water table, sources of drainage water other than deep percolation, and salinity status of soil and ground water. Soils data collection and analysis is common to all design procedures. Current investigations sample the soil to the depth of potential drain placement (2–4 m) with selected deeper samples to determine the presence of a restricting layer. The soil salinity profile above the drains is noted as part of the soils investigation to determine the need for remediation. The salinity profile below the drains should also be noted since this will be indicative of the potential salt load when the drains are operational. The salinity distribution data should be considered when selecting the drain depth placement.

The design of a subsurface drainage system requires developing criteria that specify the operation of the system and the physical configuration. The operation is characterized by establishing the water table depth at the mid-point between laterals and the drainage coefficient that specifies the maximum volume, expressed as depth, of water to be removed in a 24 h period. In arid areas an additional design criterion is the control of salt accumulation by capillary rise into the crop root zone, which is accomplished by managing the mid-point water table depth to minimize upward flow of water and salt from the shallow ground water.

The USBR recommends a minimum water table depth from 1.1 to 1.5 m below land surface midway between lateral drains, depending on the crop rooting depth. From previous experience, this should result in achieving atleast 90% of maximum crop production (U.S. Department of Interior, 1993). This mid-point water table recommendation ensures that the soil oxygen status is maintained in the root zone and reduces capillary transport of water and salt from shallow ground water into the root zone and to the soil surface due to evaporative demand.

Lateral spacing design uses either transient or steady-state design procedures. The transient design method employed by the USBR is based on the dynamic equilibrium concept, which assumes that the range of the mid-point water table fluctuation remains below the design level throughout the year and returns to the design depth position at the end of the design cycle, usually annual. The transient design starts when the water table is nearest the soil surface, generally at the end of the irrigation season, and ends when the final irrigation in the design cycle results in a buildup of the water table to the prescribed design depth. A deep percolation schedule is calculated, using a representative crop rotation, soil-water retention capacity, allowable soil-water depletion, and climate data. The deep percolation value is calculated based on the irrigation system efficiency, applied water, rainfall, irrigation water quality, and the leaching requirement derived from crop salt tolerance data (Hoffman, 1990).

A drain depth will be specified and the spacing will be calculated based on the recharge schedule and the mid-point water table depth criteria. Subsequently, the drain depth will be varied to calculate a range of depths and spacing for an economic analysis. The most economic drain depth and spacing is then selected from analyses of several drain system configurations. The USBR recommends installation of drains at a depth of 2.4 m, if possible, to provide a balance between the system cost and spacing.

Deep placement of the drains generally results in a wide drain spacing that lowers the system cost relative to shallow and therefore more closely spaced drains. However, in many cases deep placement has been shown to result in an excessive salt load being discharged with the drainage water (Ayars et al., 1997; Christen and Skehan, 2001). Shallow drain placement will result in shallower flow paths (Fig. 1) and in areas with increasing salt with depth in the soil profile will result in lower salt concentrations in the drainage water and reduced loads.

3. Controlled drainage system design

There are currently no specific design procedures for controlled drainage systems in either humid or arid regions. In humid regions the approach has been to use the same basic design procedures developed for free flowing subsurface drainage systems and to modify the drainage coefficient to reflect a worst case scenario. This was deemed to be the case when the system was operating as a subirrigation system and the design rainfall occurs (Fouss et al., 1990). Under these conditions extended waterlogged periods would be a possibility and adopting this criterion should result in reduced drain spacing to accommodate the higher drainage coefficient needed to minimize the waterlogged period.

This humid region criterion is not applicable for design in arid irrigated regions, because active subirrigation will generally not be practiced except in the case of organic soils. The water table position may be maintained to improve in situ use of ground water by the crop but rainfall will generally not be a significant source of excess water during the irrigation season. If it is, then rainfall contributions to deep percolation should be included in the deep percolation schedule and drainage system design.

In arid irrigated regions the subsurface drainage system design should proceed using procedures developed by the USBR or a local agency. This will include the detailed geologic and soils evaluations and the accompanying hydrologic investigations. For new system designs the approach needs to be that the irrigation and drainage systems become an integrated water management system. This implies interactivity between the operation of the irrigation system and the management of the drainage system. In this instance, the drainage system will be managed to control the flow and water table depth in the course of time in response to the irrigation management and deep percolation. A schematic of the design process for both traditional and controlled drainage is given in Fig. 3 (Hornbuckle, 2003).

Christen and Ayars (2001) describe the development and implementation of best management practices (BMP) that provide a basis for the design of drainage systems in irrigated areas. The initial step in the design process will be to minimize deep percolation losses through improved irrigation water management (source control) by improving irrigation system design and management. After source control has been implemented, a decision will need to be made regarding reuse of the drainage water for irrigation or stimulation of in situ use by the crop through control of the water table depth. In situ use by the crop will affect the drainage design by reducing the irrigation requirement and the deep percolation losses that will be included in the drain system design procedure. Ayars and McWhorter (1985) demonstrated that the drain spacing can be significantly increased when in situ crop water use from shallow ground water is included in the deep

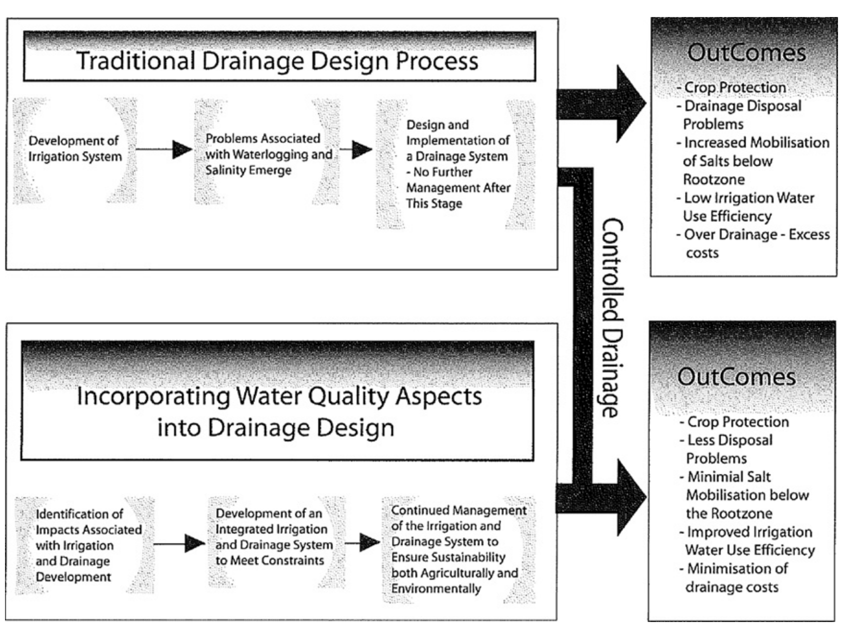

Fig. 3 – Schematic of process for developing design criteria for traditional and controlled drainage systems.

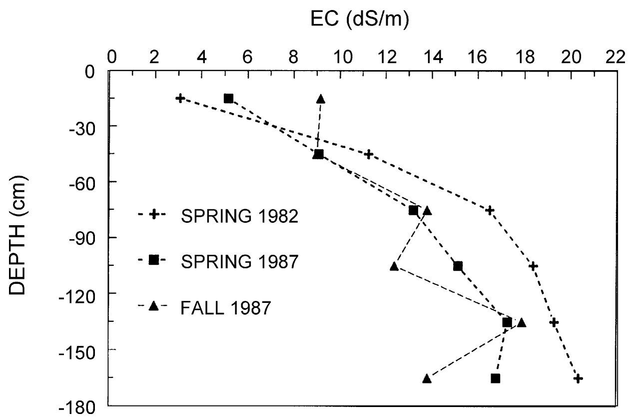

Fig. 4 – Typical soil salinity profiles in the San Joaquin Valley showing salinity response to furrow irrigation over a 5-year period.

percolation schedule. The selected water management strategies will be incorporated in the deep percolation schedule used for the drainage system design. The resulting schedule will then include the crop rotation, the irrigation and ground water quality, the irrigation system efficiency, the crop salt tolerance, and the projected in situ use of shallow ground water by the crop.

The criteria to be used in the drain depth and spacing design will be established after the drainage objectives and system operation have been developed. The mid-point water table position has generally been the starting point in the drain spacing design in irrigated areas. As previously noted, the USBR mid-point water table depth criterion is 1.1 m depth at the end of the design period using the dynamic equilibrium concept. A lateral depth of 1.9 m or larger was recommended to minimize the installation cost by maintaining a wide drain lateral spacing.

However, studies by Grismer (1989), Ayars et al. (1997), and Christen and Skehan (2001) demonstrated that deep and wide drain lateral placement increases the total salt load being discharged. It may also result in excessive drainage water volumes. It is important to understand that in arid and semi-arid environments soil salinity can increase significantly with depth, as demonstrated in Fig. 4.

Another approach to maintaining the lateral spacing is to modify the criterion for the mid-point water table depth. Reducing the mid-point water table depth from 1.1 to 0.9 m will increase the drain spacing. Ayars et al. (1997) used Hydrus-2D to model the effect of water table and lateral depth criteria on required drain spacing assuming irrigation efficiencies of 60% and 80% for a clay loam soil. The results of these simulations are summarized in Table 1.

The traditional design is characterized by a drain depth of 2.4 m with a mid-point water table depth of 1.2 m and an irrigation efficiency of 60%. When the drain lateral depth is reduced to 1.8 m and the criterion for the mid-point water table depth is 0.9 m, there is a reduction of 71 m in the required drain spacing. However, improving the irrigation efficiency from 60% to 80% results in an increase of the required drain spacing of 219 m, which is approximately 100 m less than improving the efficiency at the original drain and water table depth. However, there will be a marked improvement in the water quality, using the new criteria compared to the previous criteria, as well as a reduction in the total flow.

Controlled drainage should also result in reduced volumes and salt concentrations of the drainage water, as a result of the modification of the flow pattern due to ground water ponded over the drainage laterals. Christen and Skehan (1999) in a controlled drainage study showed that drain flow salinity was proportional to the water table depth (Fig. 5) and hence limiting drainage discharge with a deep water table will reduce the salinity of drainage waters.

Controlled drainage may be an option with an existing drainage system, as well as a new system, if the existing system can be adapted to control the water table without waterlogging a portion of the field. Alternatives include blocking selected drain lines as well as installing control structures on individual drains or the submain collector. Wahba et al. (2005) used DRAINMOD-S to demonstrate the effect of doubling the drain spacing by blocking every other drain and modifying the drain depth by installing control structures. Their results demonstrated that implementation of these measures would result in reduced drainage flow and lower irrigation requirements without a yield reduction.

4. Engineering modifications

The most obvious modification will be the inclusion of a control structure in the drainage system. There are no controls when subsurface drains discharge directly to ditches. In these situations it is possible to provide control structures in the ditches that will control the water table position in the drains upstream from the control structure. This approach is used in the flat coastal areas of North Carolina (Fouss et al., 1990). In pumped drainage the control is set by the limit switches that turn the sump pump on and off. Control of the water table at the sump is possible by repositioning the limit switches, but is only feasible in flat lands because of the alignment of the

Table 1 – Summary of drain spacing calculated using drainage criterion to account for water quality

Drain depth (m)	Water table depth (m)	Soil type	Drain spacing (m)	
			Irrigation efficiency for 60%	Irrigation efficiency for 80%
1.5	0.9	Clay loam	160	320
1.8	0.9	Clay loam	228	447
2.4	0.9	Clay loam	380	625
2.4	1.2	Clay loam	299	542

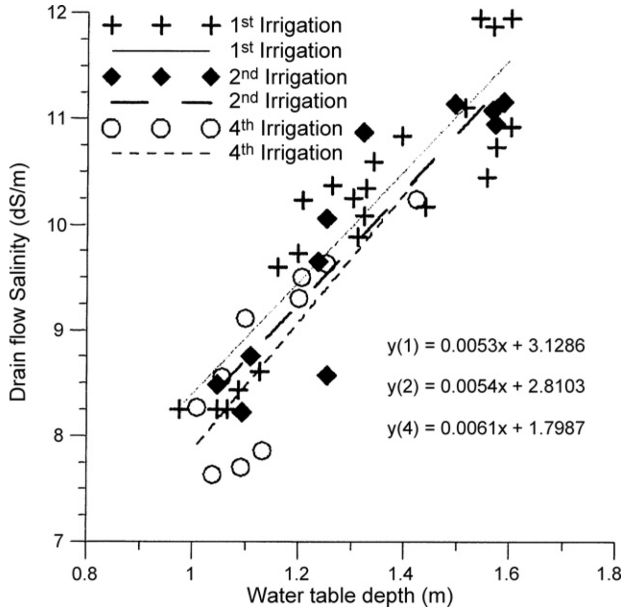

Fig. 5 – Dependence of drain flow salinity on water table depth for individual irrigation events, for drains 1.8 m deep and 20 m apart.

subsurface drains relative to the grade of the field surface. This approach has been used successfully in the Murrumbidgee Irrigation Area of Australia on a vineyard, resulting in an 88% reduction in drainage flows (Christen and Skehan, 2000).

When the drain laterals are aligned with the surface grade, as was the case in the above example, a control structure or change in limit switches at the lower end of the field will have limited effect at the upper end of the field. If the surface slope increases and, if the depth is set too shallow, waterlogging may occur at the lower portion of the field. Consider an 800 m long field having a surface slope of 0.1% with the water table controlled at a depth of 1.2 m at the lower end of the field. This will result in a depth of 2 m at the upstream end. If there is significant crop uptake from shallow ground water, this will create significant differences in the crop irrigation requirement across the field. If more uniform control is desired in such cases, control structures have to be distributed along the length of the drain, which will be more costly and create obstructions in the field.

The alternative in new designs is to install the drains parallel to the surface contours and install the submain collector perpendicular to the soil surface contours. This may require increasing drain depths across the field to insure the grade needed to carry drainage water to the outlet. In this configuration control can be established on each drain or a group of drains depending on the surface slope (Ayars, 1996). Bouwer (1955) found that installing drainage systems either perpendicular or parallel to the surface contour did not affect the drainage capacity of the system. At the time of the study (1955) installation of drains on the contour was not considered practical and it was recommended to place them at an angle between 10 and 30 degrees to the contour lines. This would be an alternative for lateral placement in future controlled drainage systems.

The design of control structures is quite flexible and should depend on the situation. There are commercially available weir type structures that have been used in the mid-western U.S. Hornbuckle et al. (2005) fashioned a control structure for individual drains, using PVC pipe as shown in Fig. 6. Ayars (1996) used butterfly valves on individual drains and a weir structure on a submain collector to control several laterals.

5. Drainage system management

Controlled drainage brings up the issue of drainage system management, which is a developing concept, particularly in arid areas. So far, use of controlled drainage systems in arid and semi-arid irrigated areas has been limited primarily to research applications. However, there is the potential to use controlled drainage commercially in situations where disposal of saline drainage water is restricted to the farm unit because of the lack of a regional disposal capability. In this situation minimizing the total flow and salt load for disposal will be

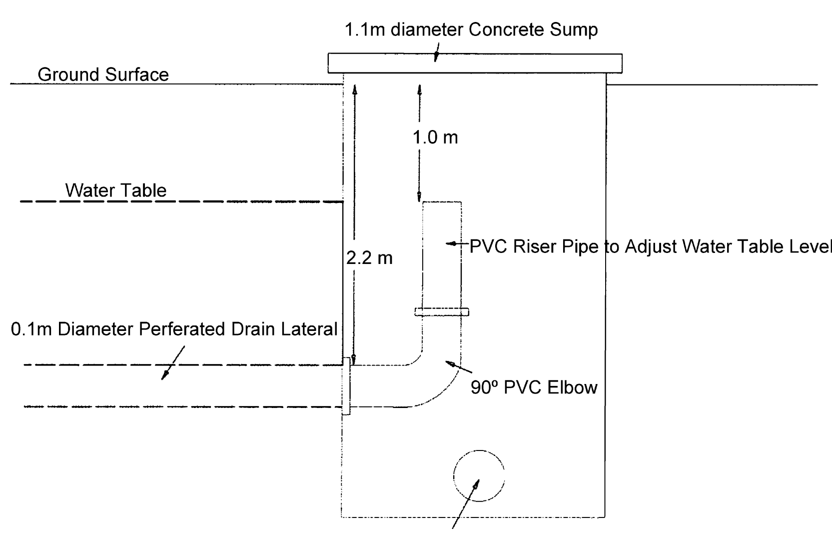

Fig. 6 – Schematic of PVC control structure used on individual laterals for controlling subsurface drainage flow.

Table 2 – Percent crop water use from shallow ground water after Ayars et al. (2006)

Crop	Water table depth (m)	Ground water quality (dS/m)	Ground water use (%)
Corn	0.6	0–6	0–58
Corn	1.05	0–6	0–29
Cotton	0.9	0.9–6	37
Cotton	2.7	0.9–6	28
Sugar beet	1.6	Non-saline	63
Alfalfa	0.4–2.1	Non-saline	28–57
Wheat	0.9	0.5–5.2	53

critical to the successful operation of the on-farm drainage disposal system and controlled drainage systems will be a necessary part of the on-farm water management.

Traditional drainage system management amounts to simply letting the system run continuously without any control, which is deemed necessary to prevent waterlogging and soil salination. It is also the practice during leaching of salinized soil. However, management measures are needed to regulate flow and reduce the impact of saline drainage water on the environment (Hornbuckle et al., 2004). There needs to be a transition from no or passive management to active management with defined water management objectives. The goal may be to reduce total drainage flow, reduce contaminant load, improve irrigation efficiency, or some combination of these outcomes. Active management of a drainage system and the water table position will contribute to each of these goals. As a guide to possible strategies, we summarize some recent research results.

5.1. *Crop water use from shallow water table*

Managing the water table position will provide the opportunity to increase in situ crop water use, which should result in improved irrigation efficiency, and reduced drainage flow and contaminant load (Ayars and Meek, 1994). The effectiveness of drainage system management will depend on the crop, the ground water quality, and the water table position. The better the match between the ground water salinity and the crop salt tolerance, and the closer the water table is to the bottom of the root zone, the better will be the opportunity for in situ crop water use (Ayars et al., 2006). Table 2 summarizes the crop water use from saline water for several crops as a function of ground water quality and depth to ground water.

The utility of controlled drainage in meeting crop water requirements depends on the source of shallow ground water. If excess deep percolation from inefficient irrigation is the primary source of ground water then improving irrigation efficiency will limit the amount of water available for crop use. The combination of improved irrigation efficiency and in situ use has the potential to significantly reduce drainage flow. If the ground water source is a result of lateral inflow then in situ use may be a significant contributor to reducing the drainage volumes. The initial geologic and hydrologic studies should provide the information to determine the source of ground water, so that proper planning and design will be possible.

Salinity management in the crop root zone is essential for the sustainability of irrigated agriculture and is a major consideration when proposing controlled drainage practices. Research has demonstrated that water and salt will move upwards from shallow ground water and may result in salinized soil in a short time. However, there has also been much research over the years demonstrating that salinity in the root zone can be effectively managed from year to year by irrigation, taking into account rainfall events (Fig. 4) (Rhoades, 1989; Rhoades et al., 1989; Ayars and Schoneman, 1986).

It has also been shown that plants are considerably more salt tolerant that previously considered and that the salt tolerance varies over the growing season (Maas and Grattan, 1999; van Schilfgaarde et al., 1974). Crops are most sensitive at germination and become progressively more tolerant as the season progress (Shalhevet, 1994). This means that salinity management should strive to remove salt from the seed bed to insure germination and stand establishment. Also, it is the average root zone salinity that affects the crops ability to extract water (Shalhevet, 1994), which means there are many options for managing irrigation systems to maintain yield without requiring large salt discharges.

5.2. *Ground water salinity stratification*

The better the match between the ground water salinity and the crop salt tolerance, the better will be the opportunity for in situ crop water use (Ayars et al., 2006). In the past the quality of shallow ground water has not been accurately represented, especially the water at the shallow ground water surface which is the layer with which plant interaction occurs. Usually ground water quality is measured infrequently and at a single depth, often well below the phreatic surface. However, by frequent and multilayered sampling a better representation of shallow ground water quality can be obtained. Northey et al. (2006) demonstrated an increase of salinity in the shallow ground water under furrow irrigated fields in the Murrumbidgee Irrigation Area in Australia. Salinity stratification of the ground water occurs due to incomplete mixing between the fresher irrigation water above the wetting front and the more regional saline ground water. This has also been reported in California (Rhoades, 1972) and the Indus river basin (Saeed et al., 2003; Asghar et al., 2002). Depending on the nature of recharge and discharge events, soil characteristics and climatic conditions, this stratification may persist beyond a

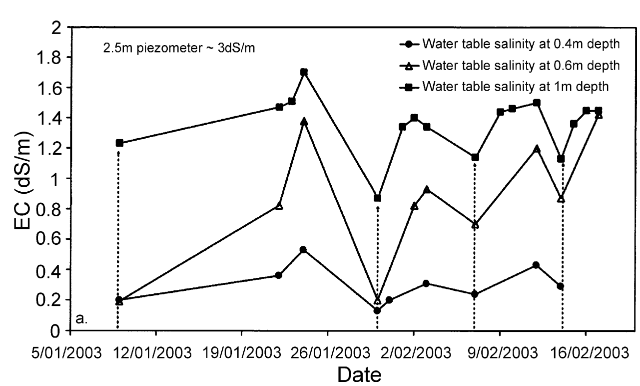

Fig. 7 – Ground water salinity variations with depth under a maize crop 2002/2003 in the Murray Darling basin. Irrigation events indicated by arrows (after Northey et al., 2006).

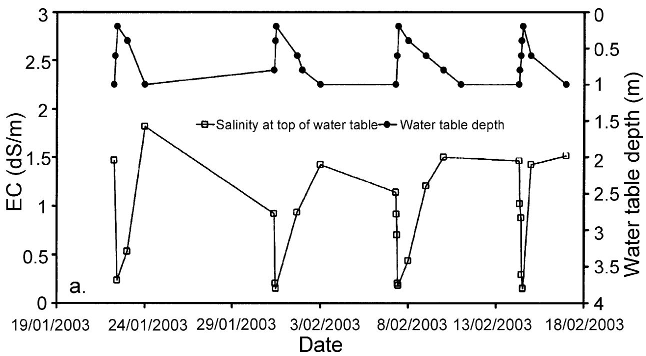

Fig. 8 – Salinity variations at the top of the water table for maize crop 2002/2003 in Murray Darling basin (after Northey et al., 2006).

single irrigation season. Northey et al. (2006) show how the salinity of the ground water varies with depth across time and with irrigation (Fig. 7). Salinity increases with depth, as is common in irrigated areas.

Since stratification has been found to be present at the beginning of and throughout the irrigation season, it is likely that it prevails throughout the year. Stratification may be the reason irrigated agriculture can persist under shallow water table conditions. Capillary upflow from a fresher layer at the top of the shallow ground water will limit the salinization risk and the potential for crop damage.

The top layer of the shallow ground water is a dynamic zone, reflecting the interaction between the ground water, soil water and the infiltrating irrigation water. Processes occurring in this zone, such as mixing, solute transport, interactions with the soil matrix, and fluctuations in the water table may result in salinity variations over short time periods. Changes in water table position and salinity at the top layer of the ground water are illustrated in Fig. 8 (Northey et al., 2006). A rising water table consistently corresponds to a decrease in salinity at the top of the ground water. As the water table declines, salinity in the upper part of the ground water steadily increases. Large fluctuations in the salinity of the top of the shallow ground water were apparent at four sites over relatively small changes in water table position and persist throughout the year.

An understanding of the salinity stratification of the shallow ground water (Fig. 7) and the short-term fluctuations after irrigation (Fig. 8) can assist in drainage design and management. Drainage systems can be designed to intercept the shallower less saline ground water and also drainage management can be used to make the less saline shallow ground water after an irrigation event remain available to a crop for use by capillary upward flow. Calculations of capillary rise and salt accumulation from different depths in the shallow ground water and at different times would result in very different analysis of soil salinization risk and crop water uptake rates.

6. Field studies of controlled drainage

For controlled drainage to become an accepted practice it will have to be demonstrated over a wide range of crops, soils, and ground water qualities. Questions that need to be answered include: what is the water table response to management, what is the modification of total drain flow, what changes occur in water quality, and what is the effect on soil salinity? Studies conducted in the United States and Australia provide initial answers to these questions for irrigated agriculture in both annual and perennial crops. The results of some of these studies are summarized in the following subsections.

6.1. *Water table response*

A 2-year controlled drainage study was conducted in the Broadview Water District in the San Joaquin Valley of California on a 60 ha subsurface drained field. The field layout is shown in Fig. 9. The drain laterals were laid in an east–west direction with the surface grade being in the south to north direction. The laterals discharged into a submain that carried the drainage water to a pumped sump in the northeast corner of the field. The depth of drains was approximately 2 m with adequate grade to insure flow through the system. A butterfly valve was installed on each lateral and three control structures were installed on the submain collector drain. An array of observation wells was installed in both 1994 and 1995. The 1994 array was centered on three drains on the south side and one drain on the north side of the field (Fig. 9) and the 1995 array was distributed across the field (not shown in Fig. 9). The depth to water table was measured weekly throughout the growing season, using a sounding device.

In 1994 the valves were closed on each lateral following the installation and were opened at the end of the growing season prior to harvest. In 1995 the valves on the laterals were not closed but the weirs along the mainline were used to adjust the water depth at 1.2 m below the soil surface at the weir located in the manhole. The water table was maintained throughout the growing season and the weirs were removed in September to lower the water table in preparation for harvest.

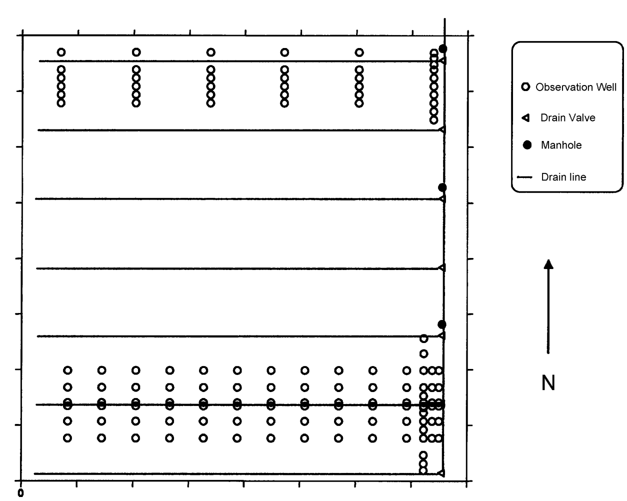

Fig. 9 – Field layout of drains, water control structures, and observation wells on Broadview Water District controlled drainage project. The observation wells show the 1994 installation pattern.

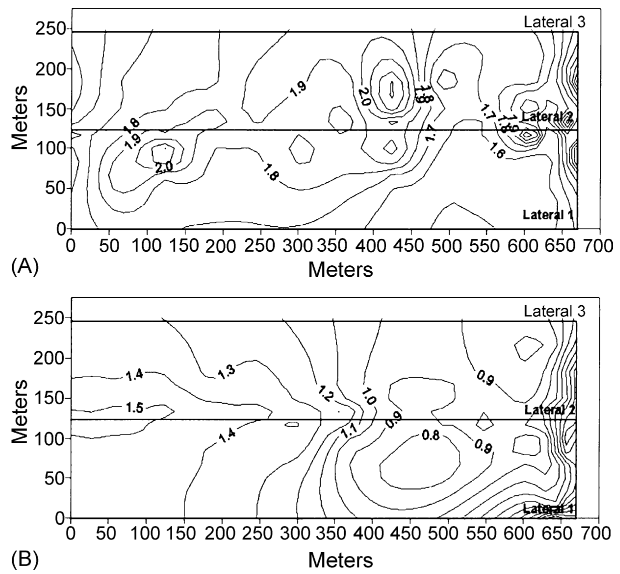

Fig. 10 – Depth to water table (m) on 21 April (A) and 2 May (B) 1994.

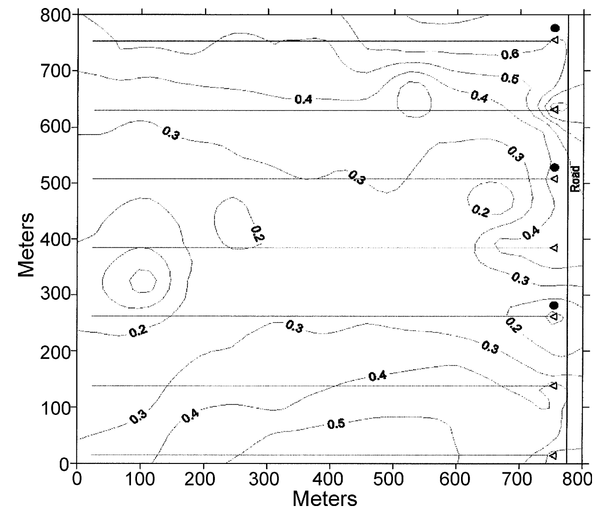

Fig. 11 – Change in depth (m) of the water table from 21 June to 13 October 1995 in controlled shallow ground water management project showing an increase in depth of water table.

The effectiveness of water table control on three laterals is demonstrated in Fig. 10. The water table depth ranged from 1.6 to 2 m below the soil surface prior to closing the valves.

After the valves were closed, the water table rose to approximately 1–1.5 m below the soil surface. The excess water needed to do this was a combination of deep percolation losses from surface irrigation and lateral flow from adjacent fields containing high water tables. This level was maintained until August when the valves were opened. Opening of the valves resulted in a increase of the water table depth of approximately 0.7 m across the field.

In 1995 only the weirs were used to control the water table position across the field the depth of the water table ranged from 1.2 m to approximately 2.2 m in the deepest area on the opposite side of the field from the controls. Fig. 11 gives the change in water table depth from 21 June to 13 October 1995. The drawdown is reasonably well distributed across the field and behind each of the control structures (dark circles on Fig. 11).

6.2. *Total flow and drainage water quality*

Reducing total flow from a drainage system will be necessary when there is a need to reduce the total load of a contaminant being discharged for disposal. Conceptually, it is apparent that by controlling the water table at a depth above the drains there will be less soil volume drained and thus less total water being discharged. However, there are still opportunities for lateral flow to be intercepted by the drainage system which may result in only minor reductions in total flow. The following sub-subsections provide examples of the effect of controlled drainage on drainage volumes, salt load, and salt accumulation in the soil profile.

6.2.1. *Improved subsurface drain design and management in the Murrumbidgee Irrigation Area*

Christen and Skehan (2001) evaluated improved subsurface drain design and management in the Murrumbidgee Irrigation Area in a replicated field trial over a 3-year period from 1996 to 1998. They evaluated unmanaged deep drains (1.8 m deep), managed deep drains (1.8 m deep), and unlined mole drains installed at 0.7 m depth. The deep drains were slotted PVC pipe. The mole drain and the unmanaged deep drain had unrestricted flow while the managed deep drain only flowed when the water table depth was less than 1.2 m from the soil surface and not at all during the actual irrigation events.

The drainage treatments resulted in markedly differing drainage volumes, salinities, and salt loads summarized in Table 3. The total volume differences were a result of the flow behavior of each of the treatments. The unmanaged deep drains ran continuously throughout the irrigation season, while the managed deep drains ran for a significantly shorter time and the mole drains had a very short flow time. A typical drainage hydrograph for a single irrigation event is shown in Fig. 12 for each of the systems.

The data in Table 3 show that the unmanaged drains had the largest flow and highest average salinity, which resulted in the largest amount of salt discharged. The data for the managed and unmanaged drains demonstrate the effect of water table control on the average salinity. The data in Table 3 demonstrate that in cases where the soil salinity increases with depth, as was the situation at this site, controlling the water table depth results in reduced salinity in the drainage water. Controlling the discharge and reducing the salinity in

Table 3 – Summary of drainage volume, salinity and total salt load

Drainage treatment	Total drainage (mm)	Average drainage salinity (dS/m)	Total salt load (kg/ha)
Deep drains	70	11	5867
Managed deep drain	47	7–8	2978
Shallow drain	15	2	319

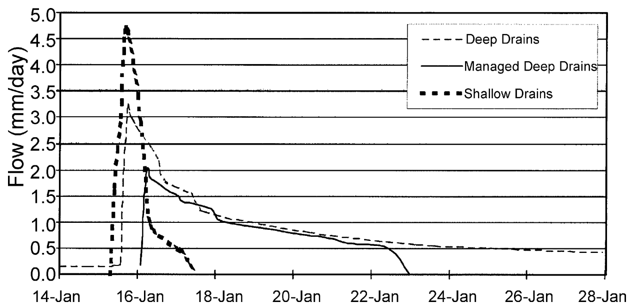

Fig. 12 – Drainage treatment hydrographs during and after irrigation on 15 January.

the drainage water resulted in a 49% decrease in the salt load being discharged. There was no significant impact on soil salinity due to the controlled drainage. Salt accumulation in the soil profile is a possibility if management measures are not implemented.

6.2.2. *Effect of controlled drainage on total flow and drainage water salinity from an established vineyard*

In another study in Australia, Hornbuckle et al. (2005), Hornbuckle (2003) demonstrated the effect of controlled drainage on total flow and drainage water salinity from an established vineyard. The drains were installed several years after the vineyard was planted. Three laterals were permitted to flow freely (F) with the next four laterals (C1, C2) being controlled at the outlet (Fig. 13). There were a total of three treatments each comprised of two laterals. One of the free flowing drains was not included in the experiment and the remaining laterals were used as described in Fig. 13. The experiment was conducted over a 2-year period in 2000–2001.

The drainage and salt load from the individual treatments as percentages of irrigation are summarized for the 2 years of the study in Table 4. The data show that the percentage drainage for the free flowing treatments was much larger than that for the controlled treatments. As a result, the salt load as a percentage of the applied salt was also very small for the controlled treatments. The value for flow from the free flowing drains was considerably less than the 14–22% of applied water that is typical for this area. This is a result of significantly reduced annual irrigation amounts of approximately 350 mm compared to previous annual applications of 600–1000 mm and to lower than average rainfall for the 2-year period.

The data for the salt load removed highlight the potential for salt accumulation in the crop root zone due to the upward flux of water from the shallow ground water to meet crop water requirements. The soil salinity data in Fig. 14 for this experiment demonstrate the potential for salt accumulation in each of the treatments.

There was a general increase in salinity in all layers with larger increases in the upper layers particularly in the 0–0.3 and 0.3–0.6 m depth layers. These increases were found in both the free draining and the controlled drainage treatments. This was a result of the increased use of shallow ground water and deficit irrigation practiced during this time period. The salt accumulation did not affect yields in this short time but may pose a threat to long-term sustainability. Long-term studies will be required to validate that approach. Modeling studies may also be used in conjunction with the field studies to evaluate the concept. Salt management in the shallow soil profile is possible through the use of pre-plant irrigation, rainfall in fallow periods, irrigation during dormancy, or by providing a leaching fraction during regular irrigation.

7. Summary and conclusions

Improved water management in arid and semi-arid irrigated regions will require development of an integrated water management system that includes the design and operation of the irrigation system and the design and active management of the subsurface drainage system. Drainage has been recognized as a requirement to sustain irrigated agriculture but poor irrigation management results in an excessive

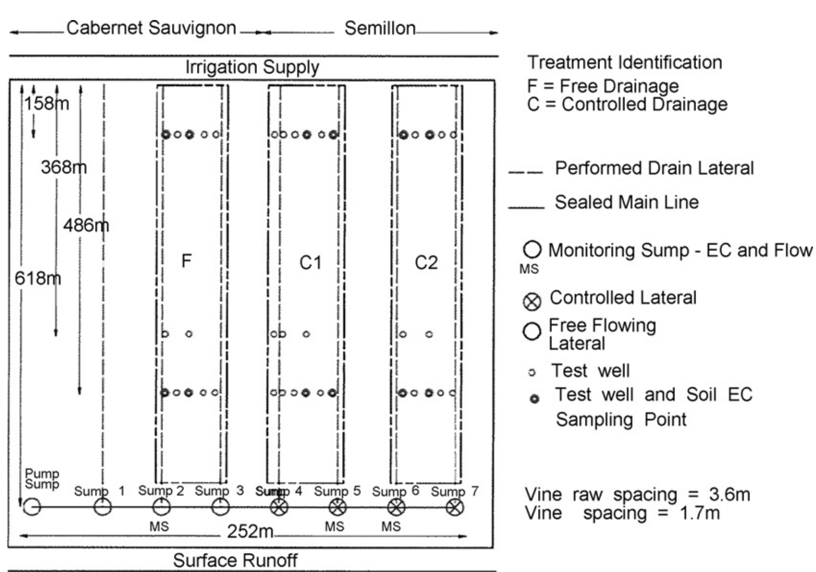

Fig. 13 – Schematic of controlled drainage study in vineyard in Murrumbidgee Irrigation Area, Australia.

Table 4 – Drainage as a percentage of irrigation and salt loads as a percentage of salt applied for two seasons

Plot	Irrigation (mm)	Drainage (%)	Salt load (%)
F	638	6	101
C1	694	0.5	5
C2	665	0.5	6

The irrigation depths are the sum for 2 years.

drainage requirement and hence over-design and large drainage volumes. This can be partially addressed by the introduction of drainage management structures, but improved irrigation management to acceptable levels of efficiency is still an essential objective. This then allows drainage design and management within the reasonable bounds expected for long-term salinity control.

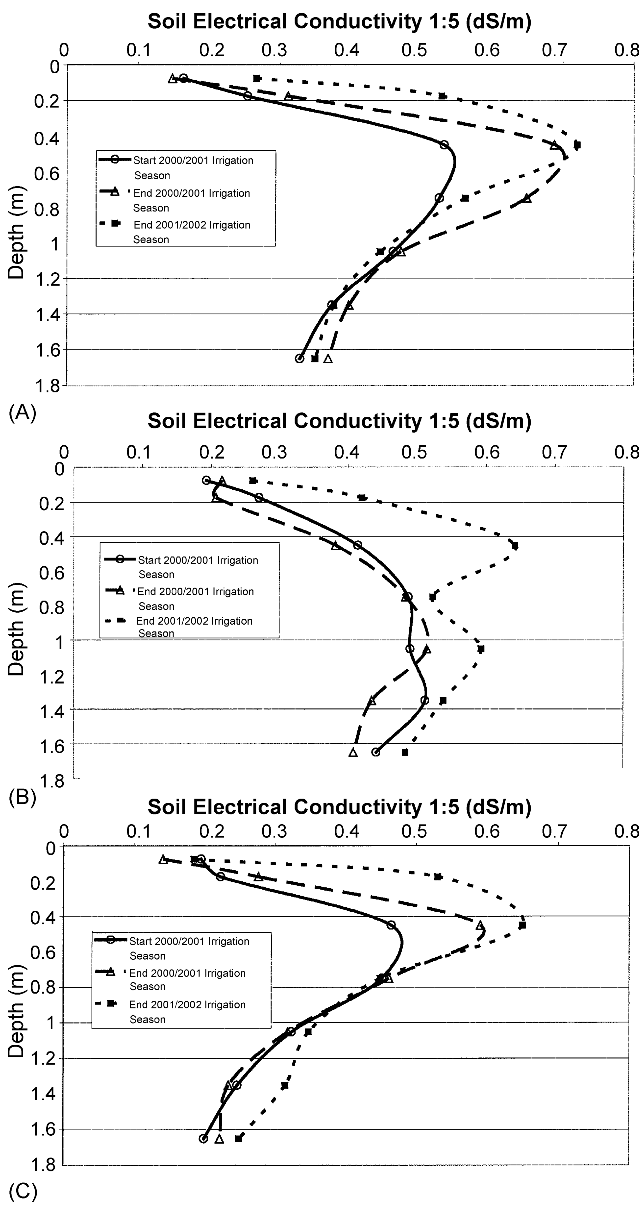

Fig. 14 – Soil salinity changes during the experimental period in (a) free flowing treatment, (b) controlled treatment 1, and (c) controlled treatment 2.

Research has demonstrated that the existing design criteria and procedures result in excessive drainage water volumes and salt loads being discharged with a significant negative impact on the quality of the receiving surface- or groundwater. The current design practices favor deep placement of drainage laterals and a mid-point water table depth between laterals in excess of 1.2 m. Model studies and field research have demonstrated that shallower placement of drainage laterals and reduced depth to mid-point water table will result in reductions in drainage volumes and salt loads. Salt accumulation in the root zone is managed through pre-plant irrigation and rainfall. Relaxing the mid-point water table depth offsets the reduction in lateral spacing when using a shallower lateral placement.

Structures for the control of the water table position should be required in new drainage system design and should be considered for retrofitting on existing systems when practical. Controlling the water table depth will improve in situ crop water use and reduce total drainage flow. Field studies have demonstrated significant in situ crop water use from capillary rise by a wide range of crops. Water table control will also eliminate over-drainage and the discharge of water in excess of that which is needed to provide good aeration of the root zone. Studies in California demonstrated that water table control was possible and effective on a 60 ha field. Field studies in Australia also demonstrated that water table control was possible in vineyards without negative impacts.

Irrigated agriculture will continue to play a significant role in meeting the world's food supply, and, for it to be sustainable, drainage must also be provided. There are at present no generally accepted design criteria for controlled or managed drainage systems in either humid or arid areas. Thus, there is a pressing need to develop new design criteria and management methods for controlled drainage systems to contribute to meeting the challenge of a sustainable irrigated agriculture that has minimum impact on the environment.

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